

X-43A Project Overview

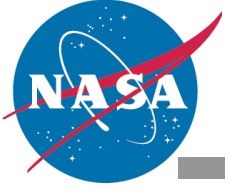
Adventures in Hypersonics



Based on AIAA Papers:

Chief Engineer's View of the NASA X-43A Scramjet Flight Test (AIAA-2005-3332)

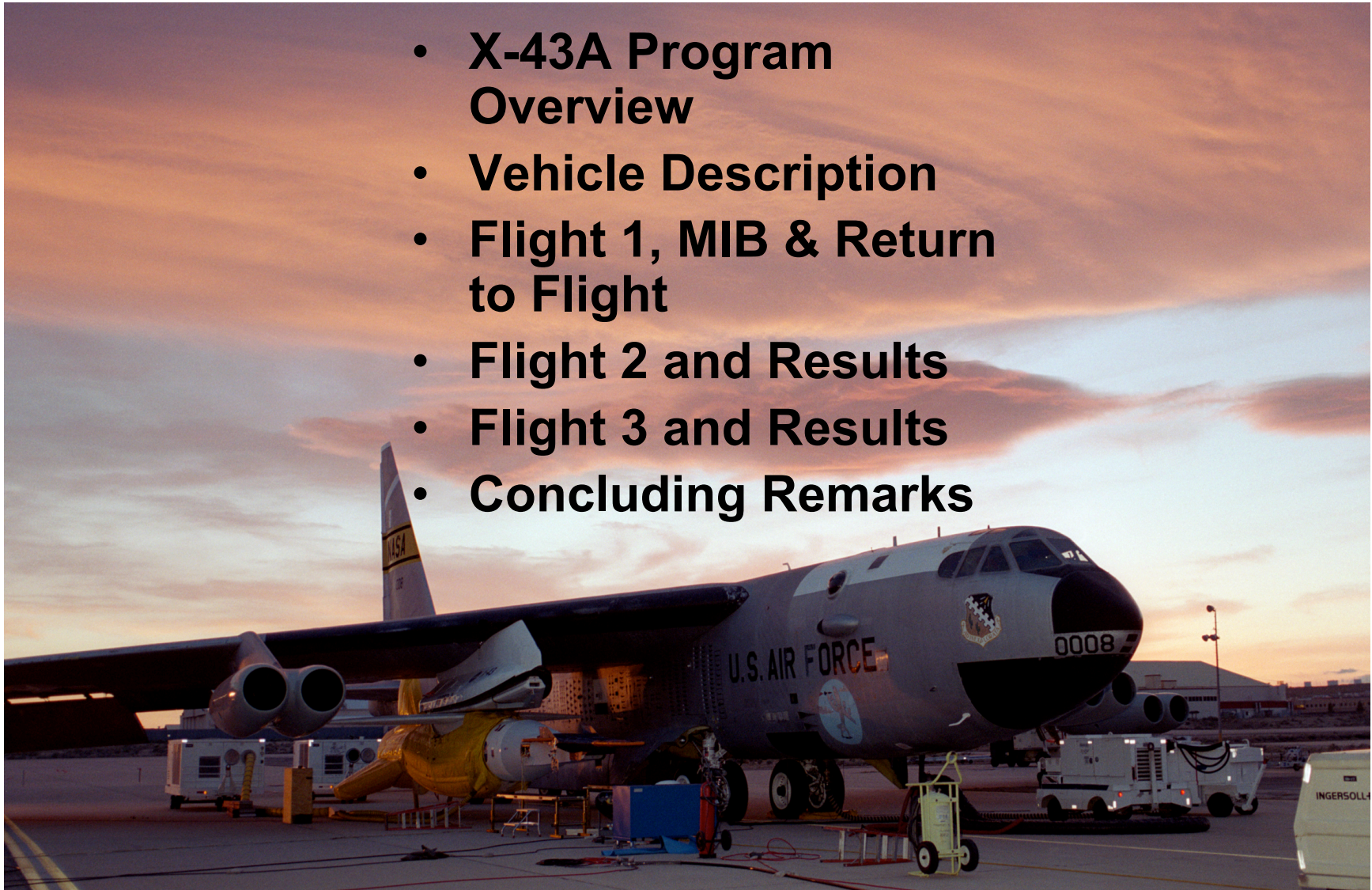
Overview with Results and Lessons Learned of the X-43A Mach 10 Flight (AIAA-2005-3336)



Presentation Topics



- X-43A Program Overview
- Vehicle Description
- Flight 1, MIB & Return to Flight
- Flight 2 and Results
- Flight 3 and Results
- Concluding Remarks



Hyper-X

X-43A (Hyper-X) Program Overview

- First ever flight demonstration of an airframe-integrated scramjet powered hypersonic vehicle
- Primary objective was to validate the tools, test and analysis techniques, & design methods of scramjet powered, hypersonic vehicles
- Three flight project
 - Two flights at Mach 7
 - One flight at Mach 10

Hyper-X Research Vehicle (HXRV)

Research Vehicle Adapter

Hyper-X Launch Vehicle (HXLV)

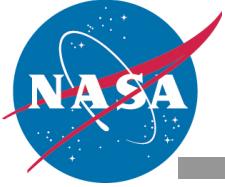
Hyper-X Research Vehicle (HXRV): ATK-GASL

- Hydrogen fueled scramjet engine
- Scaled version of a Mach 10 "cruise" configuration

Hyper-X Launch Vehicle (HXLV) - OSC

- Air launched from NASA's B-52
- Boosts HXRV to test condition
- Modified 1st Stage Pegasus booster

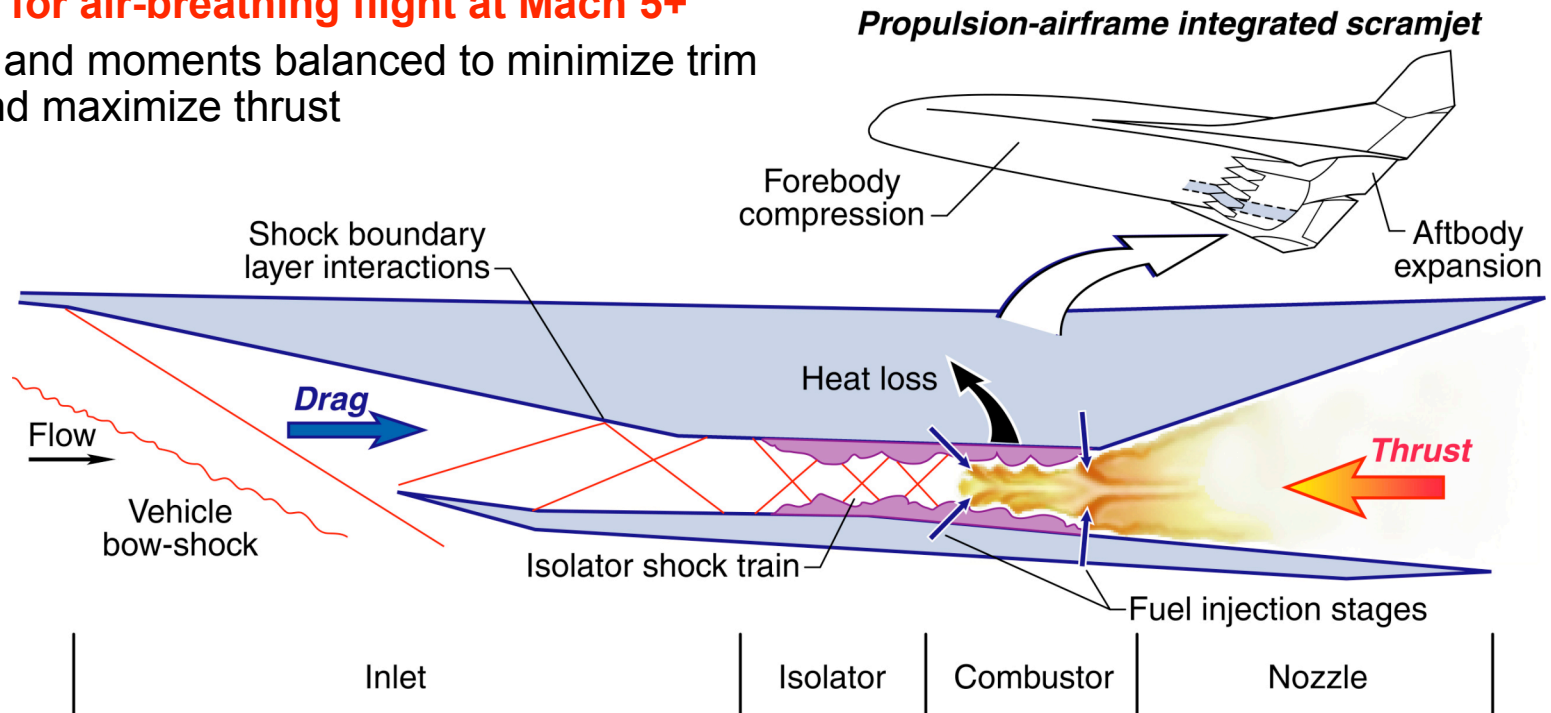
Hyper-X



Scramjets

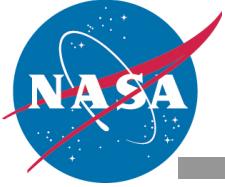


- **Allows for air-breathing flight at Mach 5+**
- Forces and moments balanced to minimize trim drag and maximize thrust

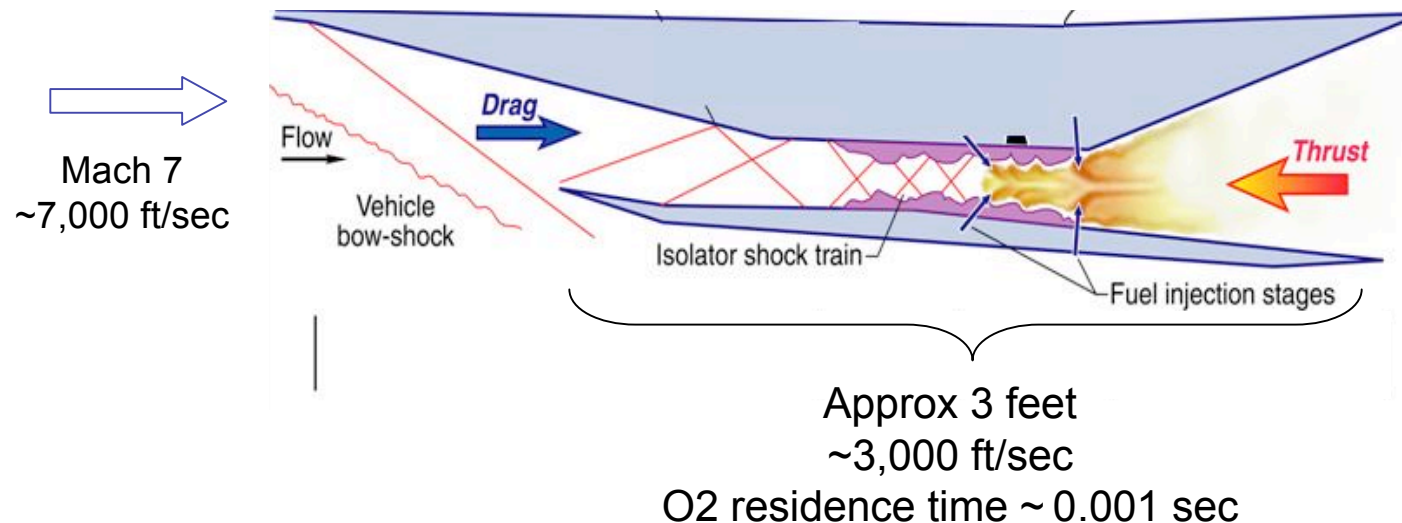


- Inlet: slows the flow efficiently
- Isolator: contains the precombustion shock system
- Combustor: injects, mixes, flameholds, and burns with minimal losses
- Nozzle: expands the gases without quenching the reactions
- All this must be accomplished in as short a distance as possible

Hyper-X



The Challenge

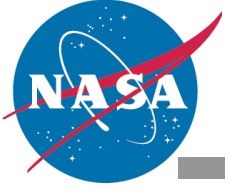


“Likened to keeping a candle lit in a hurricane”

- During the 0.001 sec
 - Inject the H₂, mix the fuel and air, and ignite the mixture
 - Combust the H₂+O₂ to H₂O (a min of 7 reactions modeled in CFD codes)
 - Maintain flameholding and don't unstart (propagation of shock train forward)
 - Expand the gases and extract the energy to produce thrust > drag
- Accomplish at Mach 7 speed and dynamic pressure of 1000 lb/ft²



Hyper-X



X-43A Flight Phases



Captive Carry to Launch Condition



Boost to 100,000 feet



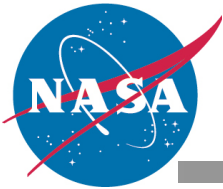
MACH 7/10 Separation



Free Flight & Scramjet Operation



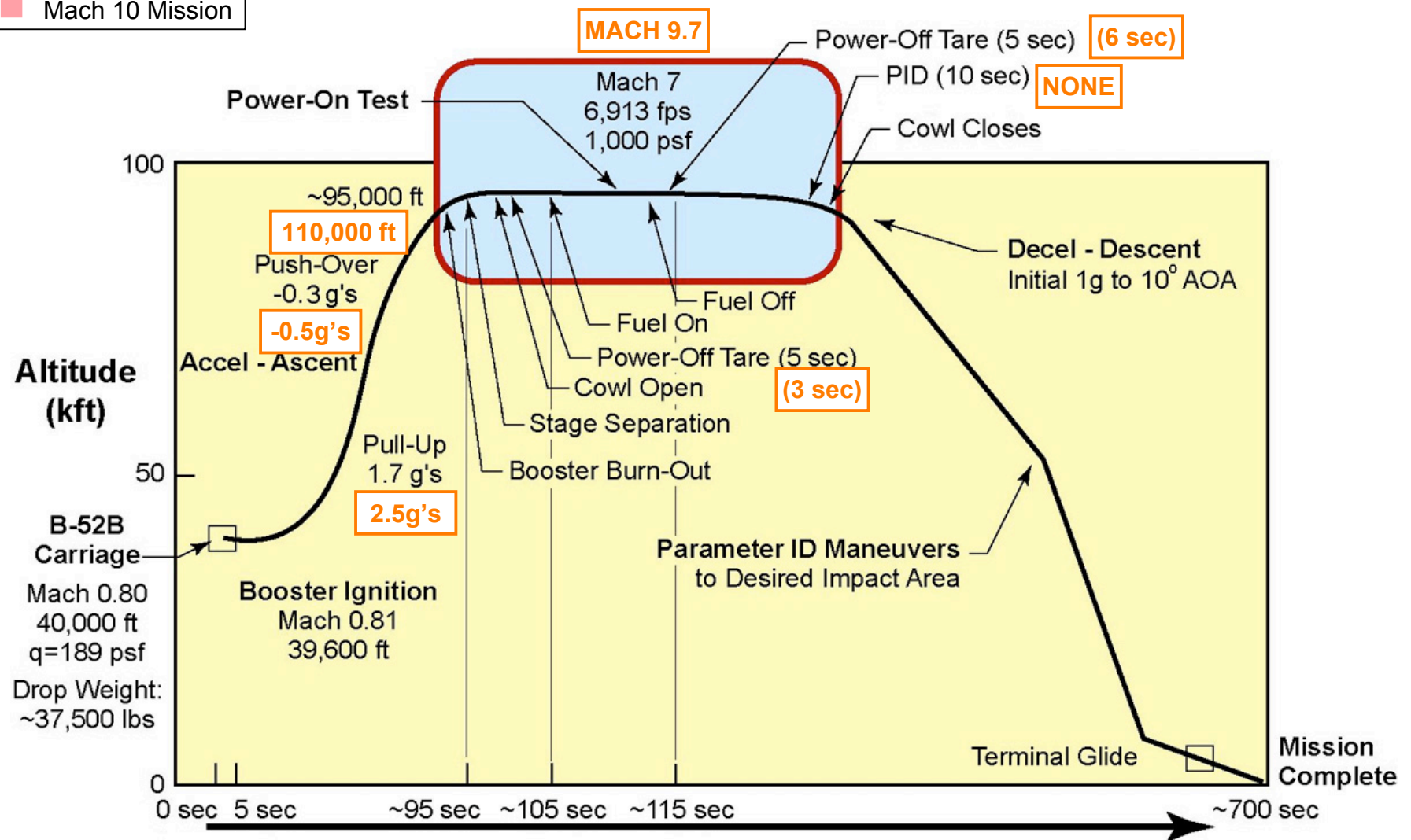
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X-43A Mach 7 and Mach 10 Mission Profiles



- Mach 7 Mission
- Mach 10 Mission



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Nominal Timeline



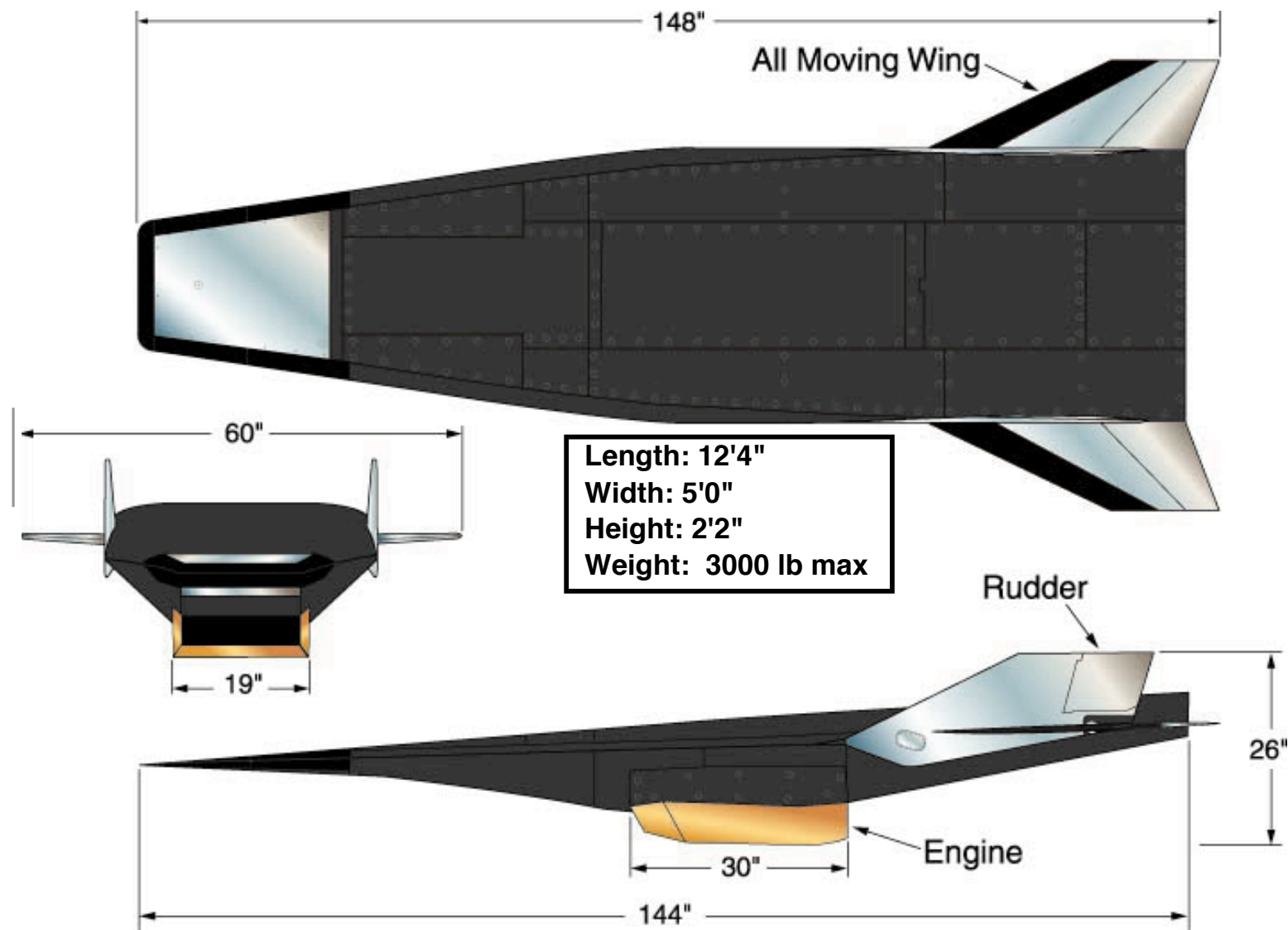
| Event | Flight 2 | Flight 3 |
|------------------------------------|--|--|
| Ground ops | days | days |
| Captive carry | 1 hour | 1 hour |
| Drop | 5 sec | 5 sec |
| Boost | 93 sec | 88 sec |
| Separation Event | 2.5 sec | 2.5 sec |
| Cowl open | Cowl open | Cowl open |
| Pre-experiment tare | 5 sec | 3 sec |
| Ignition w/ H ₂ /silane | 3.5 sec | 4.5 sec |
| H ₂ fuel burn | 7.5 sec | 4.5 sec |
| Post-experiment tare | 4 sec | 6 sec |
| Cowl open PID | 17 sec | None |
| Cowl closed | Cowl closed | Cowl closed |
| Cowl closed PID's | Performed at every Mach no. from Mach 5 to 2 | Performed at every Mach no. from Mach 8 to 2 |
| Splash | 10 minutes after Sep. | 12 minutes after Sep. |



Hyper-X



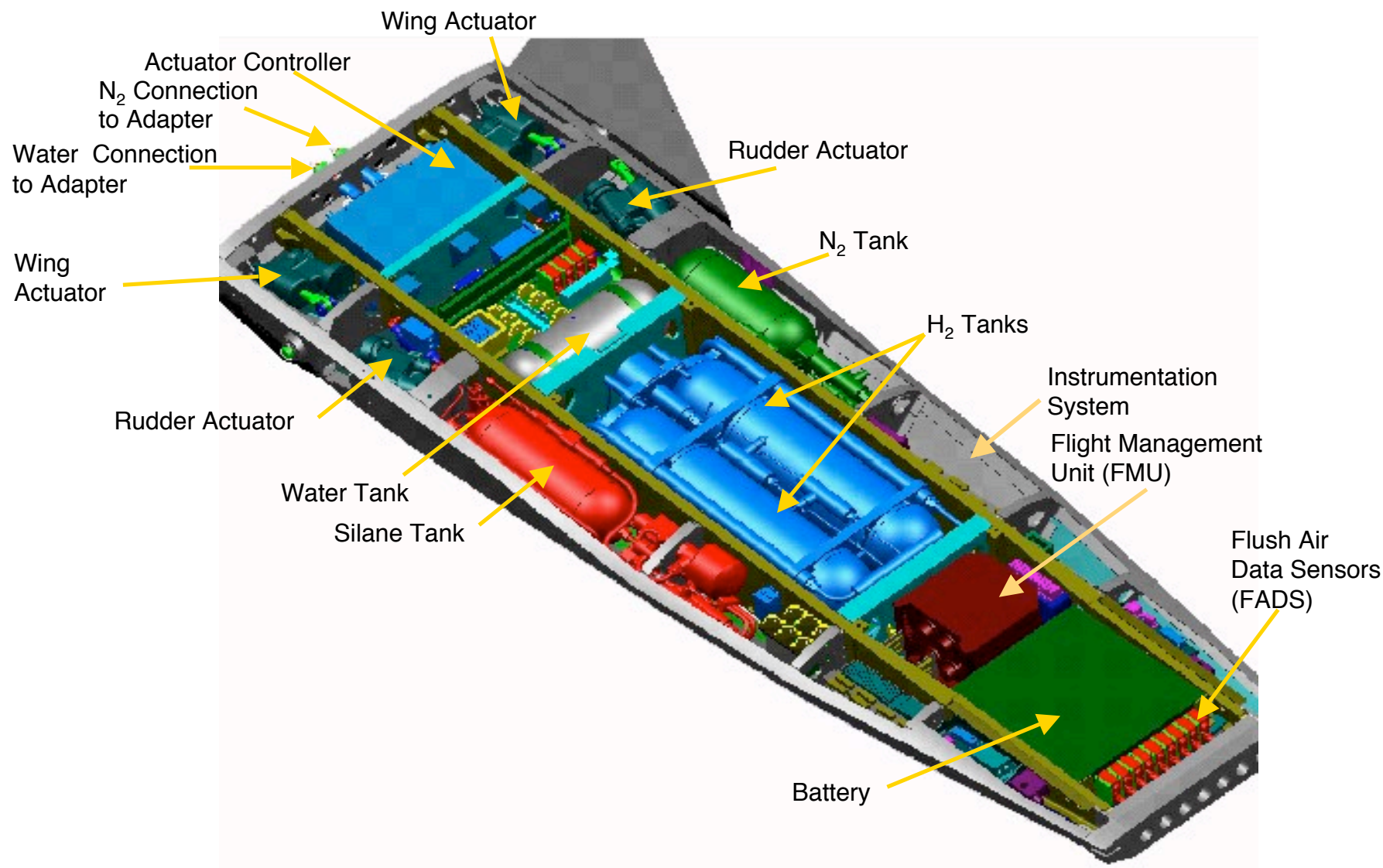
X-43A External Vehicle Configuration



Hyper-X



X-43A Internal Vehicle Configuration



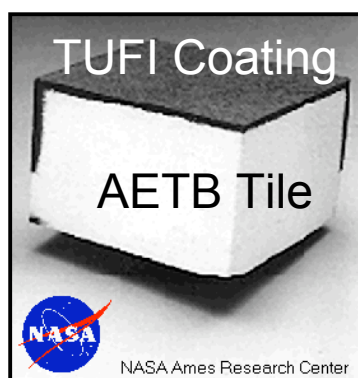
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X-43A Material Layout



- | | | | |
|---|--------------|---|---------------|
|  | Tungsten |  | Carbon-Carbon |
|  | TUFI/AETB |  | Copper Alloy |
|  | Haynes Alloy | | |



TUFI =Toughened Uni-piece Fibrous Insulation
AETB=Alumina Enhanced Thermal Barrier

Carbon-Carbon

Nose
Leading
Edge



Side
Chine



Hyper-X

NASA Dryden Flight Research Center
Edwards, CA

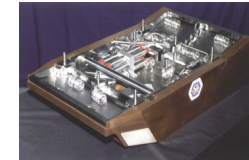


*Research/Flight Operations
Airworthiness, Flight Safety, Range Safety*

The Hyper-X Partnership

Drawing on Expertise from Coast-to-Coast

ATK - GASL
Ronkonkoma, NY



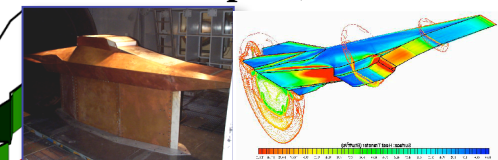
Engine & Fuel Systems

'It takes a village'

Air Force Flight Test Center, Vandenberg AFB
Naval Air Warfare Center, Pt. Mugu
Pacific Sea Range

Boeing
St Louis, MO
Technology Design

NASA Langley Research Center
Hampton, VA

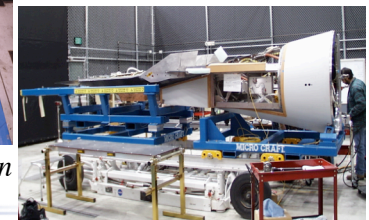


Technology Design and Experimental Test

NASA Marshall Space Flight Center
Huntsville, AL
Architecture Studies and Technology Assessments

ATK - GASL
Tullahoma, TN and Huntsville, AL

*Research and Launch Vehicle Interface
Stage Separation Testing*



Systems Installation

Honeywell
Clearwater, FL
Research Vehicle Flight Computer

Lockheed Martin
Dallas, TX
Wind Tunnel Testing

Orbital Sciences Corp.
Chandler, AZ



Launch Vehicle Development

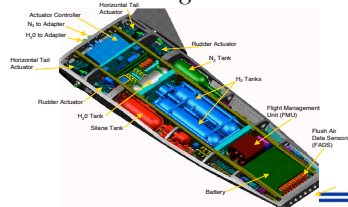
ATK
Magna, UT
Rocket Motor

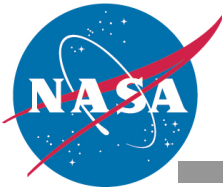
MicroCraft
Ontario, CA



Airframe Assembly

Boeing
Long Beach, CA
Systems/Software Design and Integration



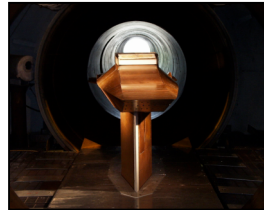


Highly Integrated Effort Required



Propulsion

- Fuel system
- Scramjet engine
- Propulsion control laws
- Environmental system



LV, Sep. & RV Sims

- GNC & PSC design & testing
- Monte-Carlo analyses
- Vehicle performance
- S/W & H/W testing
- HIL/AIL testing
- Mission control room training

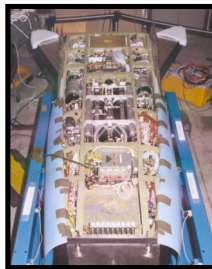
Stage Separation

- Never been done
- High q, asymmetric bodies



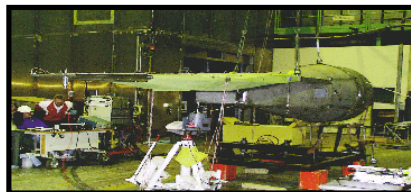
Systems

- Flight computers
- Actuators
- Power
- Software
- V & V testing



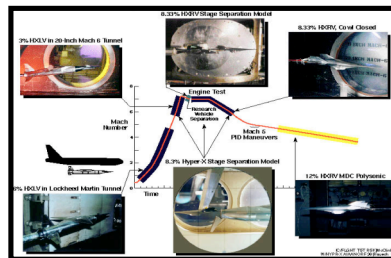
Structures

- Aero & thermal loads
- FEM modeling
- Structural analysis & design



Aerodynamics

- Outer mold line design
- Aero data base – testing & CFD



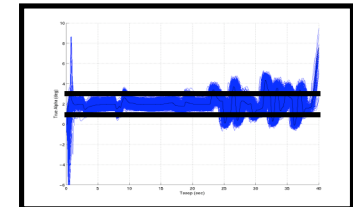
Flight Operations

- Puts it all together
- Vehicle integration, fueling, flight, ground, & control room ops



GNC

- LV, Sep, & RV control laws

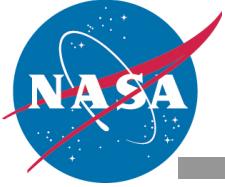


Launch Vehicle

- The ride to Mach 7 and 10
- Modified Pegasus booster



Hyper-X

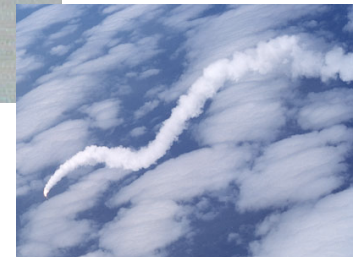
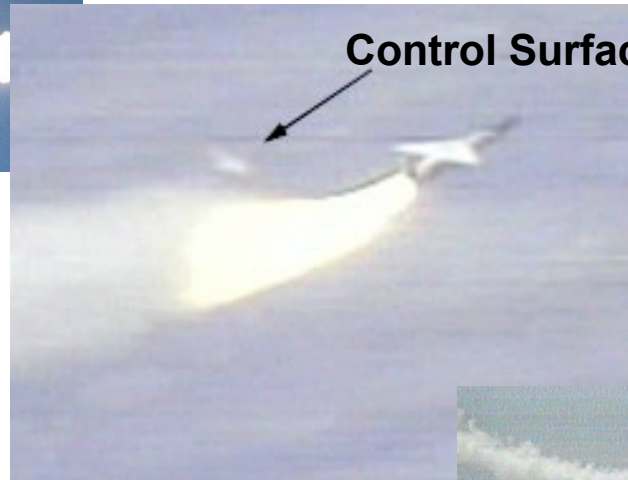


Flight 1 - June 2, 2001

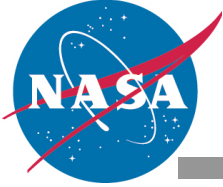


Flight Testing IS Risky Business

- Approximately 13 seconds after launch, booster departed from controlled flight.
- The right fin broke off, followed within one second by left fin and rudder.
- HXLV FTS was initiated 48 seconds after launch and caused the uncommanded “separation” of the X-43A.
- The X-43A continued to transmit data until 77 seconds after launch, which is consistent with the time splash occurred.



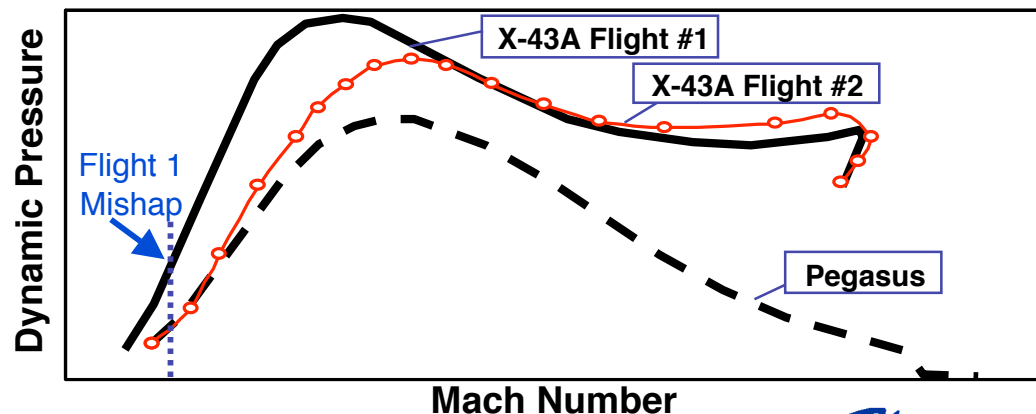
Hyper-X



Mishap Investigation & Return to Flight Effort



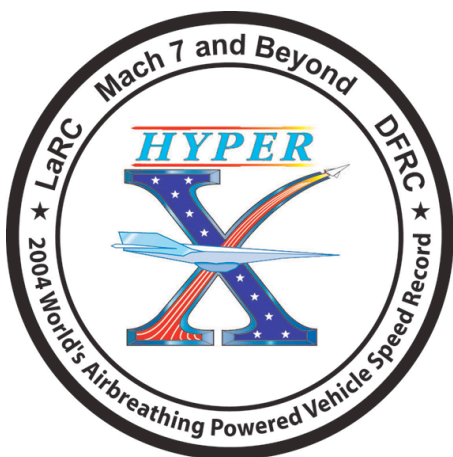
- X-43A Mishap Investigation Board (MIB) was immediately convened following the accident on June 5, 2001 and ended 9 months later.
- *“The X-43A HXLV failed because the vehicle control system design was deficient for the trajectory flown due to inaccurate analytical models which overestimated the system margins” -- Root Cause MIB Report dated 5/8/2003*
 - Modeling deficiencies caused an over-prediction of autopilot stability margins: Aerodynamics, Compliance, and Fin Actuation System
- Return to Flight (RTF) commenced March 2002 (lasted 2 years)
 - Developed a Corrective Action Plan in response to the MIB findings/recommendations
 - Developed an overall approach and roadmap for Return to Flight
 - Focused on the root causes and applied lessons learned on the HXLV to the HXRV



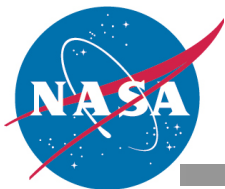
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Flight 2 – March 27, 2004



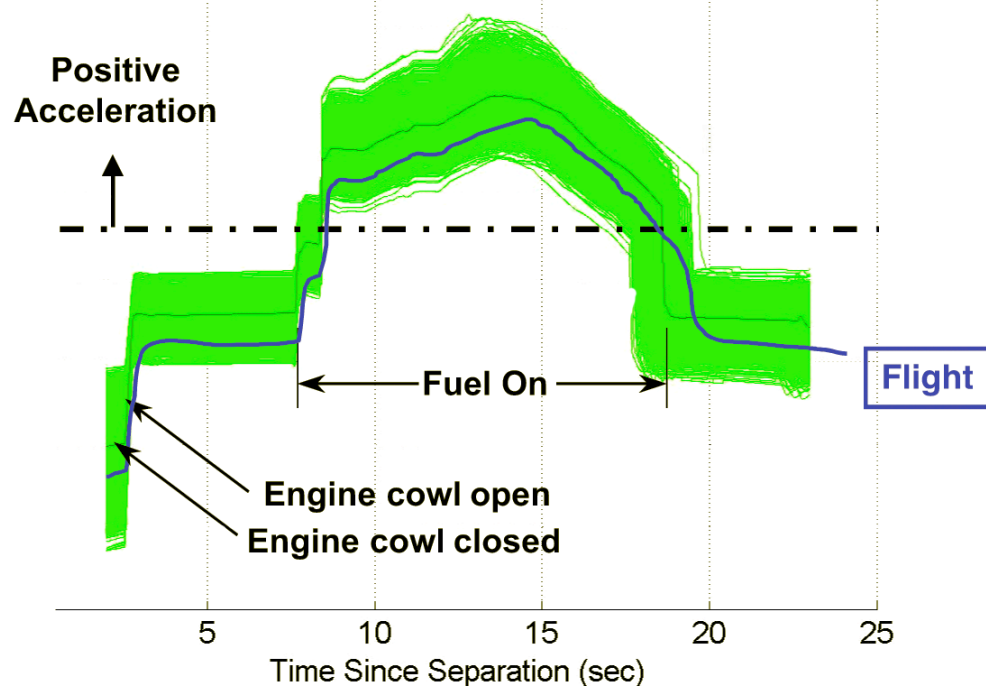
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X-43A Research Vehicle Results



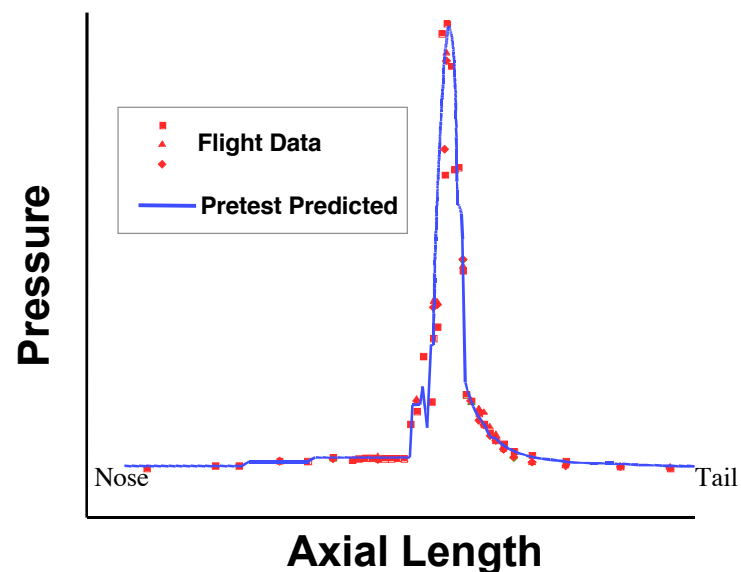
Preflight Nominal & Monte Carlo Predictions vs Flight Data



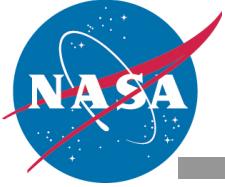
Note: Unclassified "Approximate" Monte Carlo Simulation and relative flight "Trends," NOT Data

Acceleration vs. time

Centerline wall pressure



Hyper-X



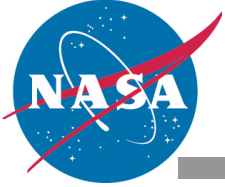
Why Did Flight 2 Succeed



- We were given a second chance and the core team was left intact
- Strong foundation based on Flight 1 experience, MIB findings and recommendations, and RTF Approach
- Strong technical expertise between NASA, ATK, & Orbital
- Strong teamwork within NASA and between NASA, ATK, and Orbital



Hyper-X



Flight 2 Results Summary



Stage Separation:

- All launch vehicle separation conditions were essentially nominal and within the specified tolerance.
- The X-43A successfully separated from the launch vehicle and achieved stable free flight throughout the engine test.

X-43A Powered Flight (Scramjet Engine Experiment):

- Scramjet engine performance was within 3% of preflight predictions – sufficient to overcome additional airframe drag and produce net positive thrust.
- Scramjet engine test conditions were well within preflight uncertainty levels and requirements
- The maximum powered Mach number was 6.8
- During powered flight, the X-43A flight controls maintained the desired vehicle angle-of-attack of 2.5 degrees within an acceptable tolerance.

X-43A Descent:

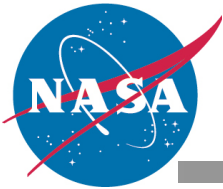
- Following the scramjet experiment, the vehicle remained controlled during the descent and successfully completed a series of descent maneuvers.

Overall Mission Comments:

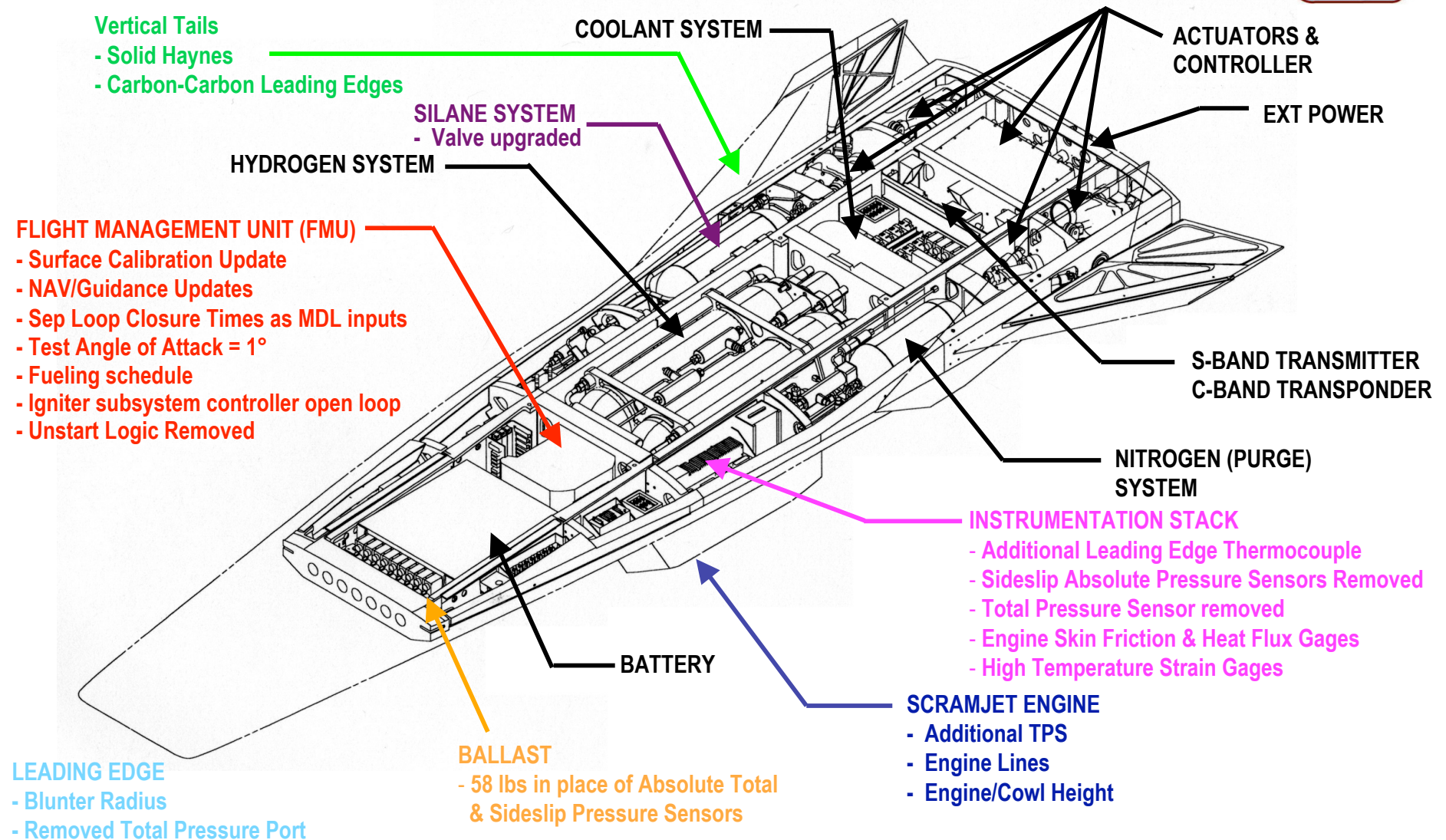
- Aerodynamic stability and control Mach 7 to Mach 0.9 – within 1 sigma uncertainty of prediction
- Boundary layer transition, boundary layer trip effectiveness – within 1 sigma uncertainty of prediction
- Airframe and wing structure, TPS and internal environment – as predicted w/ exception of rudders
- All systems on both the launch vehicle and X-43A performed well and extensive research quality data was acquired throughout the boost and descent.



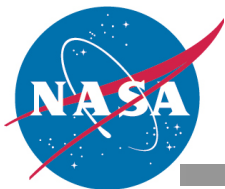
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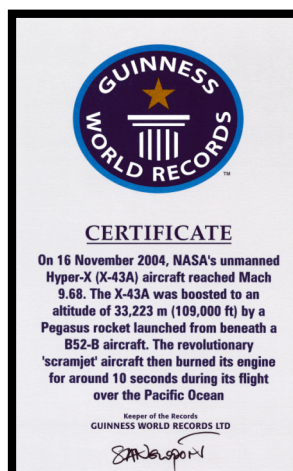
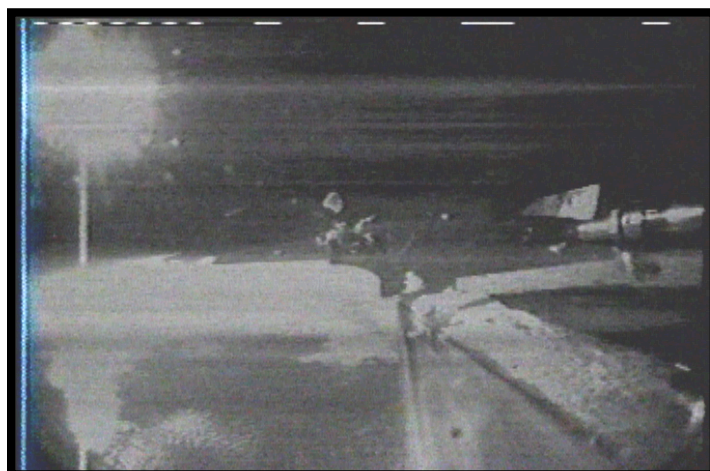
X-43A Flight 3 HW & SW Modification Summary



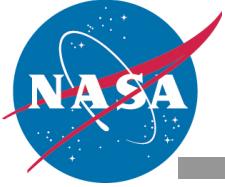
Hyper-X



Flight 3 – November 16, 2004



Hyper-X



Flight 3 Results Summary



Stage Separation:

- All launch vehicle separation conditions were essentially nominal and within the specified tolerance.
- The X-43A successfully separated from the launch vehicle and achieved stable free flight throughout the engine test.

X-43A Powered Flight (Scramjet Engine Experiment):

- The scramjet experiment/fuel on began approximately 5 seconds after separation
- The maximum powered Mach number was 9.6
- During powered flight, the X-43A flight controls maintained the desired vehicle angle-of-attack of 1 degree within an acceptable tolerance.
- The scramjet was fueled for approximately 10 seconds, providing predicted thrust.
- During this time the vehicle achieved cruise condition.
- The data collected during the engine test is by far the largest amount of data acquired for a Mach 10 scramjet. The quantity, quality, and type of the data acquired is well beyond what has been acquired in wind tunnels.

X-43A Descent:

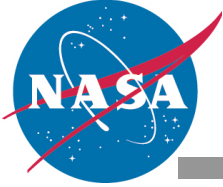
- Following the scramjet experiment, the vehicle remained controlled during the descent and successfully completed a series of descent maneuvers.

Overall Mission Comments:

- All systems on both the launch vehicle and X-43A performed well and extensive research quality data was acquired throughout the boost and descent.



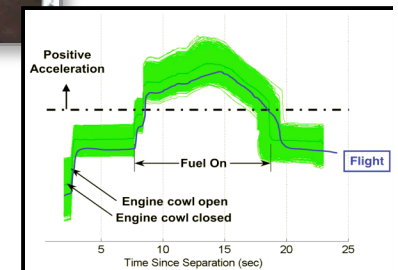
Hyper-X



Concluding Remarks



- **Best Possible Outcome: Scramjets Work & Flight Testing Is Necessary**
 - In general results were as expected for scramjet test conditions achieved however, there are some “interesting things” in the data for both flights.
- **Primary Objective Met**
 - Vehicle and engine data substantiates hypersonic vehicle and engine design tools and flight scaling methodologies.
 - The quantity, quality, and type of the data acquired during the Mach 10 engine test is well beyond what has been acquired in wind tunnels.
- **Successful Separation**
 - Confirmed that non-symmetrical high-dynamic pressure stage separation is feasible, leading the way to future safe staged launch systems.
- **Why were we successful?**
 - Rigorous processes for design, development, testing, and validation
 - Strong technical expertise and team work between NASA, ATK, GASL, Boeing & Orbital Sciences Corporation



Hyper-X